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DATA ACQUISITION AND ANALYSIS FOR THE SCIENTIFIC OBSERVATION HOLE PROGRAM, KILAUEA EAST RIFT ZONE, HAWAII

TASK 2 REPORT

for

UNIVERSITY OF HAWAII

Honolulu, Hawaii

by

GeothermEx, Inc.
Richmond, California
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January 1990

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1. INTRODUCTION

As part of the State of Hawaii's evaluation of geothermal resources, the University of Hawaii is coordinating a Scientific Observation Hole (SOH) drilling program. Four SOHs are to be completed on the Island of Hawaii in the East Rift Zone of Kilauea Volcano; each will be approximately 4,000 feet deep. These wells are being drilled to define and delineate zones with anomalously high subsurface temperatures, and to characterize the lithologic and hydraulic properties of the zones into which they penetrate.

This report is the second of three reports which describe a methodology for interpreting various types of data from the observation holes to estimate critical reservoir parameters. In the first report, the slim hole concept is discussed, the types of data to be collected are reviewed, and the assessment methodology is described qualitatively. In this report, data acquisition and analysis are discussed in detail, including chemical sampling. In the third report, a detailed well testing plan is set forth.

In the following chapter, downhole data to be collected as the wells are drilled and after well completion are described in detail. Chapter 3 provides guidelines for fluid sampling and analysis, in the event that the wells are allowed to flow. In Chapter 4, data collection and analysis from the well testing phase of the assessment program is discussed. Sample forms for data collection are presented in

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Appendix A, and a description of EPRI's Mobile Geothermal Laboratory is presented in Appendix B.

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2. DOWNHOLE DATA COLLECTION AND ANALYSIS

2.1 Introduction

Downhole data are collected and analyzed continuously during the drilling process. These data are used not only to develop a conceptual model of the geothermal system but to aid in decision making as drilling proceeds. For example, casing points are often selected on the basis of the wellsite geologist's analysis of downhole conditions.

After the well is completed, additional downhole data are collected; these data consist primarily of pressure, temperature and spinner surveys. This chapter describes in detail the downhole data to be collected, suggests methods of collection and describes how the data are used for resource assessment.

2.2 Data Collected During Drilling

Data collected during drilling is incorporated into a continuous record which describes the subsurface conditions encountered during drilling. This continuous record is often referred to as the mud log. A sample of the header page, blank data page and completed data page of the mud log can be found in Appendix A.

The header page contains basic well information, including well name, field, location, elevation, spud date, completion date, depth, log

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interval and the names of various personnel involved in the project. Certain summarized downhole data are also included on the header page; these are filled in during drilling and after completion, and include hole diameter, casing schedule, depth of lost circulation zones and depth of fluid entries.

The header page provides explanations of symbols used and units of measurement of various parameters. Space is provided to explain lithologic patterns, hydrothermal alteration patterns, mineral abbreviations and other abbreviations commonly used. At the bottom of the header page are the column headings for the data pages, including drilling penetration rate (logged either in feet/hour or minutes/foot), depth, lithology, alteration, drilling fluid temperature into and out of the hole (logged either in °C or °F), and the amount of drilling fluid lost or gained during drilling.

On the data page, space is provided to specify the range of values to be used for each quantitative parameter. These values may vary as drilling proceeds; for example, the drilling penetration rate scale may need to be modified as harder rock is encountered. Scale changes should be clearly noted.

An example of a completed data page is also included in Appendix A. This page includes typical descriptions of lithology and alteration as determined from drill cuttings, illustrating the type of description required. Lithologic descriptors include primary lithology, texture, color, hardness and mineralogical composition. Alteration descriptors include degree or intensity of alteration, matrix vs.

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interstitial alteration, and alteration mineralogy. If cores are taken, additional descriptors such as fracture frequency and direction, veining and core length should be included.

There are several additional notes which should be made on the mud log at regular intervals. These include drilling parameters such as weight on the bit (WOB), rotational speed of the kelly drive (RPM), strokes per minute of the mud pumps (SPM) and mud pump pressure (PP). Whenever a bit is replaced, the depth and time intervals over which the old bit was used and the type and serial number of the new bit should be recorded. The bearing and drift angle measured at each directional survey point should also be noted on the mud log, as should the temperatures measured by running Maximum Reading Thermometers (MRTs) in the hole. As they occur, casing points, circulation losses, fluid entries, water level measurements, and drill-stem test results should be noted. Finally, any changes in mud composition or volume should be recorded.

As drilling proceeds, data pages of the mud log are completed as described above and stored. When TD is reached, the header page of the log is completed and the pages of the log are spliced together. This continuous record is essential to the development of the conceptual model of the geothermal system.

Ideally, the wellsite geology for all SOHs should be performed by a single individual, assuring consistency in data quality. The wellsite geologist may prepare a weekly report which summarizes drilling activities, the depth interval drilled, formations encountered,

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hydrothermal alteration, temperature indications, permeability indications and any interpretation, comments or prognosis he or she may have to offer. A sample of the weekly wellsite geology report form is included in Appendix A. It should be noted that this report is not intended to be a substitute for a daily report to be prepared by the driller, which is typically oriented more toward drilling management rather than reservoir assessment.

2.3 Data Collected After Completion

The primary types of data collected after well completion are chemical samples, well test data, downhole geophysical logs, and downhole pressure, temperature and spinner surveys. The first two types of data are discussed in detail in the following chapters of this report. Geophysical logs such as caliper and cement bond logs may be run to satisfy well completion and inspection regulations. Other logs which evaluate the part of the formation which is open to the well (i.e., the uncased section of the hole) may also be run.

For the purposes of resource evaluation, temperature and pressure logs provide extremely valuable data. A sample form for downhole temperature and pressure survey data can be found in Appendix A.

If injection testing is to be carried out immediately after well completion, temperature and pressure surveys should be run before testing (after the well has been cleaned out and the mud replaced with fresh water) and during injection. After the injection testing is

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finished, downhole temperature and pressure surveys should be run on a regular basis until the well has completely recovered to static (undisturbed) conditions. GeothermEx recommends running surveys at the following times: immediately after injection, one day shut, three days shut and six days shut. If the well has not completely recovered by that time, additional surveys may be necessary.

Spinner surveys provide useful information on the location of feed zones or injection zones in the well. If a spinner tool is available, spinner surveys should be run during injection and possibly after the well is shut in. The reason for running shut-in spinner surveys is to identify zones of interflow between two or more of the well's feed points; this aids in the interpretation of static downhole temperatures.

If the wells are flow tested, a pressure, temperature and spinner survey should be run at least once during the flow test. If separate surveys can be run while the well is flowing at different rates, it may be possible to determine the flowing characteristics of more than one of the well's feed zones. This is possible because the contributions to the total flow of each feed zone will vary as the wellhead pressure (and therefore flow rate) varies.

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2.4 Data Analysis

2.4.1 Subsurface Data

The purpose of collecting downhole data is to understand subsurface conditions and to apply that understanding to the development of the reservoir model. This is accomplished by determining the relationship between downhole parameters within a single well and between wells.

As discussed in the preceding sections, downhole data are collected in various ways and recorded on various forms; however, in order to understand the relationship between data sets, they must all be examined together. At GeothermEx, we have found that an extremely useful way of presenting downhole data is to reduce all available data to one or two page-sized sheets. The result of this data reduction is referred to as the downhole summary plot.

Two examples of downhole summary plots can be found in Appendix A; the first is from a steam well at The Geysers and the second is from well HGP-A. The types of data found on these sample plots are summarized below.

- Completion data. The internal configuration of the wellbore is described by symbols representing the casing string, casing diameter, casing shoe, liner hangers, liner diameter, slotted and blank sections of liner and open hole diameter.

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- Circulation losses. Triangular symbols represent zones where fluid losses were noted during drilling. The large and small triangles indicate total and partial circulation losses, respectively.

- Lithology. Rock types, as determined from cuttings or cores, are indicated by different patterns.

- Drilling penetration rate. From the mud log, the drilling rate is digitized and plotted.

- Steam or water entries are plotted against the increase in flow line pressure which occurs as the entries are encountered.

- Percent flow. Spinner survey results are interpreted and plotted to show the relative contributions from producing zones in the well, or the relative injectivity of various zones. Raw spinner data (RPS or RPM) can also be plotted.

- Temperature and pressure data. Drilling fluid return temperatures and bottomhole temperature measured during drilling (using MRTs) are plotted, as are any temperature or pressure surveys run after completion. The well condition during each survey is noted in the plot legend.

- Notes. Completion date, workover date, or any other pertinent information which may influence data interpretation can be noted on the plot.

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Other types of data can be plotted on the downhole summary plots, including: gas data, such as methane or carbon dioxide (if gas concentration data are collected during drilling); hydrothermal alteration data (texture, mineralogy, etc.); water levels; and any other data which (because of its variation with depth) may help to interpret subsurface conditions in the reservoir.

Once all data are plotted, relationships between many of the plotted parameters can be identified. There may be correlations between:

- drilling penetration rate and lithology;
- temperature and circulation losses;
- temperature and fluid entries;
- temperature and completion details;
- circulation losses or fluid entries and spinner data; and
- numerous other downhole parameters.

Determining the relationship between parameters in a single well and from well to well is critical to the development of the reservoir model. These data define the geometry of the reservoir in

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terms of the geologic structure and stratigraphy and their relationship to temperature, pressure and fluid phase distribution.

2.4.2 Reserve Estimation

Once the conceptual reservoir model is developed and the subsurface temperature distribution defined, recoverable reserves can be estimated using the methodology developed by the U.S. Geological Survey in Circular 790 (Assessment of Geothermal Resources of the United States - 1978). In this method, the reserves of electrical energy (E) is given by:

$$E = W_A \cdot \eta_u \qquad (1)$$

where η_u is an utilization factor (less than unity) to account for mechanical and other losses that occur in a real power cycle and W_A is the available work.

W_A is given by:

$$W_A = m_{WH} [h_{WH} - h_o - t_o (s_{WH} - s_o)], \qquad (2)$$

where m_{WH} = mass of fluid produced at the wellhead,
h_{WH} = enthalpy per unit mass of fluid at the wellhead,
h_o = enthalpy per unit mass of fluid at the final state,
t_o = rejection temperature (°K),
s_{WH} = entropy per unit mass of fluid at the wellhead and
s_o = entropy per unit mass of fluid at the final state.

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The parameter M_{WH} in equation is very difficult to estimate at the early stage of development of a geothermal reservoir because the recovery factor (R_g), defined as the ratio of geothermal energy recovered at the wellhead (q_{WH}) to the geothermal energy originally in the reservoir (q_R), is not known with any certainty. The above mentioned USGS Circular suggests assuming R_g to be 0.25. We have found R_g to vary over a wide range, and therefore, we consider taking R_g equal to 0.25 a crude approximation. We prefer to estimate a range of R_g values based on a careful analysis of the conceptual model of the reservoir along with the available data base. We often resort to a probabilistic evaluation in order to quantify the uncertainty in the calculated reserves as a result of the uncertainty in R_g and certain other parameters.

The parameter M_{WH} in (2) can be estimated from:

$$m_{WH} = \frac{q_{WH}}{(h_{WH}-h_{ref})} \qquad (3)$$

where h_{ref} = enthalpy at a reference temperature (t_{ref}), which the USGS Circular 790 takes as 15°C.

The parameter q_{WH} in (3) is given by:

$$q_{WH} = R_g \cdot q_R \qquad (4)$$

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The parameter q_R in (4) is given by:

$$q_R = \rho c \cdot a \cdot d \cdot (t - t_{ref}) \qquad (5)$$

where ρc = volumetric specific heat of rock plus water,
a = reservoir area,
d = reservoir thickness, and
t = reservoir temperature.

Using equations (1) through (5) with known or assumed resource parameter values and a value of the utilization factor one can calculate the recoverable amount of electrical energy. Then, assuming a plant life and a plant capacity factor, one can calculate the maximum developable power plant capacity for the reservoir.

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3. CHEMICAL SAMPLING AND ANALYSIS

3.1 Introduction - the Mobile Lab

This chapter describes the plan for acquisition and analysis of fluid chemistry data using the Mobile Lab CHEMLAB, supplied to the project by EPRI. The Lab contains sampling equipment and an analytical chemistry laboratory in a trailer which can be sited at a well or a power plant. A summary paper and figures describing the lab is reproduced as Appendix B. Figure 1 of Appendix B is a flow chart which shows the overall capabilities of the Lab system and provides a uniform approach to sampling, stabilization, and analytical methods. The exact use of the Lab will depend on available equipment, budget, operating personnel, training, and opportunities for sample collection, which will be affected by drilling and testing scenarios yet to be determined.

The basic plan for data collection and analysis includes:

1) choosing a specific and consistent method of sample collection, in accordance with sampling conditions;

2) selecting the appropriate sampling interval and collecting the sample(s);

3) recording well and/or flow conditions and documenting the collection;

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4) stabilizing samples by physical and chemical procedures;

5) analyzing samples using the Mobile Lab and/or other commercially available field and laboratory instruments and services;

6) data quality check procedures;

7) data storage and tabulation;

8) data reduction; and

9) analysis of the data for its contribution to the reservoir assessment.

Steps 1 - 4 are discussed in section 3.2. Steps 5 - 7 are discussed in section 3.3, and steps 8 and 9 are discussed in section 3.4.

3.2 Plan for Sample Collection

The Mobile Lab is designed to obtain samples from single phase and two phase flow lines at wells, separators, in gathering systems and in power plants. Steam samples are condensed under pressure to collect condensate and non-condensible gases together or separately. Water samples are collected under pressure to prevent boiling. Liquid and steam in a two phase flow can be separated and sampled individually, under pressure. The Lab does not include downhole sampling equipment,

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but this can be added. To collect water samples after steam separation at atmospheric pressure, the sampling system will not be needed. Such samples are obtained at points of discharge such as the flowline from the well into the drilling sump (e.g., the blooie line), or the weirbox.

Samples may be collected: (a) during drilling; (b) downhole; (c) from two phase flowlines; and (d) from single phase flowlines.

3.2.1 Collecting Fluids During Drilling

Samples will be collected during air drilling if there is production of water or steam to the surface, during mud/water drilling if circulation is suspended and the hole is allowed to flow, and during any kind of drilling if the hole is unloaded by swabbing or bailing. Portions of these samples will be treated as outlined in figure 1 of Appendix B. The samples are likely to carry suspended solids and may require being centrifuged before filtration and acidification. Suspended carbonates can dissolve when dirty samples are acidified.

Drilling mud chemistry may be monitored to detect reservoir fluids by correlating changes in ion concentrations and ratios with reservoir fluid entry points. Parameters of particular interest are mud resistivity, Cl and HCO_3.

3.2.2 Collecting Fluids Downhole

Downhole sampling devices are designed to open and collect a sample at a pre-determined time or on command, after being lowered into

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a well to the desired sampling depth. Samples will be obtained from productive zones, where these have been identified and when there is a reasonable chance that good samples can be obtained. Samples collected immediately after drilling or injection and before the well has flowed are often contaminated. A wellhead sample obtained after cleanout indicates production chemistry more reliably than does a downhole sample. However, downhole samples collected at selected depths may help to define interzonal flow (flow within the well between different production zones) when the well is shut in. If scale forms in the well when it is flowed, downhole samples may directly measure the reservoir concentrations of the scale-forming species. If a hole is not flowed, it may be cleaned by natural reservoir circulation. This type of clean-out is slow, and can take over a year to become complete.

3.2.3 Wellhead Collection from Two Phase Flowlines

If a well is flow tested, the produced fluids will be sampled from the two phase flowline out of the wellhead. The Task 3 report includes a discussion of flowline systems. The exact design of the flowline will depend upon well characteristics and other factors yet to be determined.

Sampling ports will be located downstream of an orifice plate in the flowline, and upstream either near the wellhead, near the orifice, or both. In each location, there will be ports located on the top, side and bottom of the flowline, or at two positions: 45 degrees above and below horizontal. At a given test, some locations may be better for sampling the liquid phase, some better for sampling the steam

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phase, and some best when it is desired to sample both phases at the same location and at the same pressure. Therefore, the flow system is equipped with ports at several locations to meet changing conditions and special needs. Ports are located both upstream and downstream of the orifice plate (or a flow restricting valve) so that total flow enthalpy can be measured by determining the gas concentration in steam at two different pressures.

The general plan is as follows:

1) Water samples will be taken under pressure through the portable separator from a horizontal or downside port upstream of the orifice plate, and at atmospheric pressure from the weirbox.

2) Steam samples will be taken under pressure through the portable separator from a horizontal, upside or top port upstream of the orifice plate, and from the horizontal, upside or top port downstream of the orifice plate. For determination of enthalpy using the two steam samples, it will be necessary to have a pressure drop of at least 30 to 40 psi across the orifice.

Flow test designs and port locations often dictate the pressure and temperature of sample collection. However, certain conditions are optimum for the operation of a portable separator, and these will be sought during testing. The best separation temperatures range from around 140°C to a temperature some 50°C below the "enthalpy temperature" of the well. For example, if the total flow enthalpy is 320 kcal/kg (saturation temperature of 300°C), the range of separation temperatures

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should be between 140°C to 250°C (pressures from 53 psia to 225 psia). If the total flow enthalpy is only 203 kcal/kg, then the optimal temperature range is reduced to only 140°C to 150°C.

3.2.4 Wellhead Collection from Single Phase Flowlines

Single phase flowlines will exist only if: a) there is artesian flow of cold water; b) a well produces dry steam, or; c) wells are tested with a full-flow steam-water separator, which allows water and steam to be collected separately from the outlet flowlines. In such cases, samples will be collected.

3.2.5 Sampling Interval

Opportunities for sample collection during drilling or using a downhole sampler usually are limited. If opportunities arise during drilling, the plan is to collect samples frequently, because the flow may be of short duration and the composition is likely to be changing rapidly. If a well is being swabbed or bailed, a water sample may be collected each run, even if most samples eventually are discarded. If the well is flowed for a short period (say, under an hour), samples may be collected as frequently as every 10 to 15 minutes.

During a scheduled test, the rate of sample collection will decrease with time. The rate will be highest at first, to monitor clean-out and to cover the possibility that the test may have to be aborted. During a three day test, for example, samples of water and steam would be collected several times during the first day, twice

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during the second day, and perhaps only once during the third day. The exact frequency will depend upon the previous history of the well (flow or injection), and the rate of change of fluid composition (if any), as determined by analyzing certain key species (conductivity, Cl) as soon as possible after the sample is collected. Tracking of key species will occur much more frequently than signature tests (see below). Water composition will be tracked primarily at the weirbox, steam composition (gas concentration in steam) will be tracked primarily using the separation system.

3.2.6 Recording Conditions and Documenting Collection Method

Whenever samples are collected the physical conditions related to the state of the fluid will be recorded. These include:

1) recent history of the well (drilling, flow test, injection, repairs, known or suspected damage, most recent logs etc.);

2) wellhead temperature and pressure (gauge and absolute);

3) flow rate;

4) total flow enthalpy (if measured);

5) collection method and sample source (port location, weirbox, depth downhole, etc);

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6) temperature and pressure (gauge and absolute) of steam separation and sample collection;

7) downhole temperature at the production zone(s);

8) depth of downhole sample collection and temperature at that point; and

9) date and time of sample collection.

Some of this information usually is recorded somewhere in the drilling or testing program, but interpretation of chemical data is often hindered by the difficulty of accessing and compiling it from different sources. Hence, such information will be recorded and filed alongside the chemical data.

3.3 Plan for Analyses

Table 1 of Appendix B lists all of the chemical species and physical properties which the Mobile Lab can measure. Figure 1 of Appendix B shows the flow logic of a "signature test", which is considered the complete characterization of a fluid. A "tracking test" is a subset of this, during which a chosen subset of parameters is monitored at time intervals.

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3.3.1 Sample Stabilization

Stabilizing the sample when it is collected is an integral part of the analysis procedure. The methods to be used are shown in figure 1 of Appendix B. The sample portion which is acidified is to be filtered before acidification, to avoid dissolution of suspended carbonates. Samples for analysis of stable isotopes are to be collected in glass vials, others in plastic.

3.3.2 Analysis Suite

For the reservoir assessment it will not be necessary to determine all of the species and properties in table 1 and figure 1 of Appendix B. The most important are:

1) in liquids - As, B, Ca, Fe, K, Li, Mg, Na, NH_4, SiO_2, Cl, HCO_3-CO_3, F, SO_4, pH and conductivity;

2) in steam condensates - Na, Cl, HCO_3-CO_3, B and pH; and

3) in gases - CO_2, H_2S, CH_4, N_2, O_2, H_2, NH_3 and (if equipment allows) Ar.

Other elements and properties in table 1 and figure 1 of Appendix B are of little direct importance to the assessment. Total dissolved solids is better determined by summation than analysis. Analyses of the trace metals (e.g., Hg, Cr, Ni, Pb) may be needed to characterize the fluid *vis-à-vis* questions of fluid disposal.

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The Mobile Lab analysis capability does not include stable isotopes of hydrogen (deuterium) and oxygen (^{18}O). These are to be analyzed in water and steam condensate collected at the same pressure, at a commercial laboratory with good reputation in the geothermal industry (e.g., at Southern Methodist University).

3.3.3 Data Quality Procedures

Data quality checks will be used to ensure that the analytical results are consistent and reliable. The Mobile Lab procedures include a number of steps taken during analysis to insure that results are accurate (see Appendix B). Completed analyses will be screened by checking charge balance (anion to cation ratio) and comparing calculated conductivity against measured conductivity in samples diluted to about 100 micro-mho. If instructions for diluted conductivity checks are not included in the Mobile Lab procedures books, they will be taken from Standard Methods for the Examination of Water and Wastewater, by the American Public Health Association.

3.3.4 Data Storage

All final analyses and related production data (wellhead and steam separation pressure and temperature, flow enthalpy and total mass flow, downhole sample depth/temperature, etc.) will be filed into a computer data base for automated tabulation and easy retrieval, graphing, and calculations.

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3.4 Data Analysis

3.4.1 Data Reduction

To allow comparisons between samples collected at various pressures of steam separation, the samples will be reduced to a condition representing total flow. If the well produces from a single phase liquid reservoir, the total flow will be the same as the reservoir fluid composition before boiling and steam separation. If there is boiling in the reservoir and excess steam enters the well, the total flow will include the excess.

For each water and/or steam sample, the relative amounts of each phase at the collection point will be calculated. Then the separate analyses of each phase will be combined in the correct proportion. The vapor and liquid fractions will be determined from pressure and total enthalpy. The total enthalpy will be known from physical and/or chemical measurement at the wellhead. Enthalpy also will be estimated indirectly from the chemical data, using results of chemical geothermometry. There are cases where a water sample is collected without a corresponding steam sample, as from the weirbox. In such cases, the non-condensible gases are omitted from the data reduction.

A second aspect of data reduction will be to calculate various ion ratios, such as Na/K, B/Cl, SO_4/(sum of anions), which are independent of the amount of steam separation.

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Data tabulations will include both the original, "raw" sample data, and "reduced" total flow compositions.

3.4.2 Support of the Reservoir Evaluation

Geothermal fluid composition influences evaluation of wells and the reservoir, production system cost and design, scaling and corrosion, possible changes in the environment caused by fluid disposal, and design of controls to prevent such changes if deemed damaging.

Examples of well and reservoir evaluation include:

(1) determination of fluid characteristics needed for production system design (TDS, pH, total gases, H_2S);

(2) determining fluid characteristics in relation to plans for fluid disposal (toxic metals, hydrogen sulfide gas);

(3) determination of the potential for scale formation;

(4) measurement of the total enthalpy of two phase flow;

(5) use of fluid composition to calculate temperature of rock-water interaction in the reservoir;

(6) detection of higher temperatures than exist at production zones;

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(7) determination of reservoir flow directions and sources of recharge;

(8) detection of groundwater influx at field margins;

(9) detection and characterization of vertical inhomogeneities in the reservoir;

(10) determination of the flow direction and mixing of produced fluid which is injected back into the system;

(11) monitoring the backflow clean-out of fluid injected into the reservoir; and

(12) planning fluid disposal in consideration of toxic components in the water and steam.

Not all of these evaluations will be relevant or possible. In general, more information concerning the reservoir will be obtained from liquid or two phase flow than from a steam well, and more information will be obtained from flowing test samples than from downhole samples or flow during drilling.

The evaluation of geochemical data for reservoir analysis will involve comparative and quantitative procedures. Comparative procedures include tabulating data for fluids characterization and plotting key

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parameters on graphs, maps, and cross-sections. Examples of plots are:

- B vs. Cl;
- Na versus K;
- Na/K versus total dissolved solids;
- non-condensible gas concentration versus enthalpy or wellhead pressure;
- Cl versus enthalpy; and
- SiO_2 versus enthalpy.

The quantitative procedures are divided into two stages. The first stage is the data reduction discussed above. The second stage is calculations of fluid condition at various points. This starts with chemical geothermometry to estimate fluid temperature in the reservoir; these results are then compared with measured temperature. The chemical geothermometers and their governing equations are listed in table 3.1.

Depending upon data abundance, data quality and fluid characteristics, the second stage may or may not continue with estimations of silica and carbonate scaling potential, and gas partitioning during boiling and steam separation. The calculations involved are complex and illustrating them is beyond the scope of this presentation.

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4. WELL TESTING DATA COLLECTION AND ANALYSIS

4.1 Introduction

The primary type of tests to be conducted in each SOH are injection tests. These will be both short-term completion tests and long term injection tests. If possible, the wells will also be flow tested. During the long-term injection test and the flow test, observation wells may be used to monitor pressure changes across the field. During the short-term completion test, only the active well will be instrumented. Details of all well testing procedures are described in the Task 3 report.

4.2 Injection Testing

The short-term completion test and long-term injection test procedures are described in Chapters 2 and 3, respectively, of the Task 3 report. During the short-term completion test a temperature/pressure survey will be run while injecting at a relatively low rate (30-50 gpm). Subsequently, the pressure tool will be left in the hole at a specified depth while the rig's mud pumps are used to pump cold water into the well at three different rates. After the third rate-step is completed, the well will be shut-in with the pressure tool left in the hole to measure the pressure falloff.

Long-term injection tests are to be conducted on each of the SOH's for a nominal period of 30 days. The procedures to be used during

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the tests are described in Chapter 3 of the Task 3 report. During the long-term test, downhole pressure information from observation wells and the injection flow rate and wellhead pressure data from the injection well will be obtained. It may be possible to obtain downhole pressure data from the injection well provided that the ability of the well to accept water is not affected by the flow restriction caused by the downhole capillary tubing and chamber in the SOH.

The data from the above tests will be analyzed using transient pressure analysis techniques to estimate well skin factor, reservoir transmissivity (or permeability-thickness product) and reservoir storativity (or porosity-compressibility-thickness product). The use of transient pressure testing, where the pressure changes in response to a change in flow rate are measured within the well in which the change occurs and/or in surrounding observation wells, is fully described in two monographs published by the Society of Petroleum Engineers: Volume 1 (Pressure Buildup and Flow Tests in Wells, Matthews and Russell, 1967); and Volume 5 (Advances in Well Test Analysis, Earlougher, 1977). These monographs are highly recommended for further information on this subject as, in the following sections, only a few of the more important equations will be presented and discussed.

4.2.1 Short-Term Injection Testing

The pump flow rate and wellhead pressure should be monitored every five minutes during the short-term injection test, with the data recorded on the appropriate form provided in Appendix A. The charts from the Kuster downhole pressure and temperature tools should be

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interpreted at the same time intervals for the injection period and at the intervals specified on the pressure falloff test form (Appendix A) for the period after injection has ceased. The collected data from the short-term injection test are then analyzed to obtain information on the ability of the open formations to accept injection water.

Initially, the flow rates and pressures measured at each rate step are plotted on a cartesian plot. If the static pressure at the measuring depth is also known, this point is also included on the plot. From the plot of flow rate versus pressure, a best straight line is defined based on the three measured points; the injectivity index of the well, or change in flow rate divided by change in pressure, is estimated from the slope of this line.

The above discussion assumes that a straight line will be defined by the collected data. This is based on the assumptions that laminar flow occurs in the reservoir and the reservoir acts as a porous medium. Under these conditions, Darcy's law applies, which states that the rate of flow of a fluid through a homogeneous porous medium is proportional to the pressure gradient and inversely proportional to the viscosity of the fluid. Therefore a plot of flow rate versus pressure should give a straight line. However, in a significant number of field cases, it has been found that the data do not provide a good linear relationship between flow rate and pressure. It may therefore be difficult to define a reasonable straight line and hence calculate the injectivity index. Possible reasons for obtaining a non-linear relationship between flow rate and pressure are listed below.

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1. Flow in the vicinity of the well may be turbulent, causing proportionally higher pressure drops at high flow rates than at low flow rates.

2. Flow in the reservoir may be controlled by discrete fractures which may not act like a porous medium.

3. The reservoir in the near-wellbore region may be filled with mud or clay which is breaking down as a function of applied pressure. This will cause an apparent change in permeability as a function of flow rate and, therefore, the plot will be non-linear.

4. The mud and clay in the near wellbore region may be washing out due to the continued injection of cold water, resulting in a change in permeability with time. This will again cause the plot to be non-linear.

The injectivity index provides a gross measure of the reservoir capacity in the vicinity of the well; it is a function of both the permeability of the reservoir and the permeability in the near-wellbore region. The near-wellbore region may not have the same hydraulic properties as the overall reservoir due to the effect of drilling. For example, drilling or completion operations may cause a reduction in the permeability of the near-wellbore region due to plugging of pores or fractures by fine materials in the drilling muds. It is also possible that the permeability in the near wellbore region will be higher than

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the reservoir permeability, possibly due to fracturing of the rock by the drilling techniques used or due to over pressure.

To quantify the difference between the near-wellbore permeability and the bulk reservoir permeability, the concept of well skin factor is used. The well skin factor may be positive, in which case the near-wellbore permeability is less than the reservoir permeability and the well is said to be damaged. If the skin factor is negative, the well is said to be stimulated and the near-wellbore permeability is greater than the reservoir permeability. As mentioned earlier, the well skin factor and reservoir transmissivity can be estimated using pressure transient techniques.

The first pressure transient test that will be conducted will be the pressure falloff test to be run at the end of the short-term injection test. During this test, the pressure recovery at the end of the short-term injection test is monitored in the SOH. The analysis of the pressure data is based on the solution of the diffusivity equation for fluid flow in porous media. The diffusivity equation is a combination of the law of conservation of matter, an equation of state and Darcy's law. The diffusivity equation assumes: a) the flowing fluid is single phase and has small and constant compressibility; b) permeability is constant and the same in all directions (i.e., the reservoir is isotropic); c) constant porosity; and d) pressure gradients are small. For an infinite, radial system, the diffusivity equation is as follows:

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$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) = \frac{\phi\mu c_t}{k}\frac{\partial p}{\partial t} \qquad (1)$$

where: t = time;
r = radial distance;
p = pressure;
ϕ = porosity;
μ = fluid viscosity;
c_t = total compressibility; and
k = permeability.

There are numerous solutions to the above equation reported in the groundwater, petroleum and geothermal well testing literature for various initial and boundary conditions. The solutions for pressure buildup tests, which are analogous to pressure falloff tests, are well known and were first presented by Theis in 1935 and by Horner in 1951. The basic solution is as follows:

$$p_{ws} = p_i + \frac{162.6\ q\mu}{kh}\log\left(\frac{t_{inj} + \Delta t}{\Delta t}\right) \qquad (2)$$

where: p_{ws} = measured pressure (psi);
h = reservoir thickness (ft);
p_i = initial pressure (psi);
t_{inj} = injection time (hrs);
q = injection flow rate (RB/day);

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Δt = time since shut-in (hrs);

μ = fluid viscosity (cp); and

k = permeability (md).

The above solution indicates that by plotting the measured pressure against the log of the Horner time function $((t_{inj}+\Delta t)/\Delta t)$, the plot should give a straight line with a slope that is inversely proportional to the reservoir transmissivity:

$$kh = \frac{162.6\ q\mu}{m} \qquad (3)$$

where: m = the measured slope (psi/cycle).

With the above equation, the reservoir transmissivity can be estimated and it is also possible to calculate the skin factor using the following equation:

$$s = 1.151 \left[\frac{p_{1hr} - p_{wf}}{m} - \log\left(\frac{k}{\phi\mu c_t r_w^2} \right) + 3.23 \right] \qquad (4)$$

where: s = skin factor;

p_{1hr} = pressure at 1 hour after shut-in based on the semi-log straight line (psi);

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p_{wf} = pressure at shut-in (psi); and

r_w = wellbore radius (feet).

Analysis techniques based on the use of log-log plots have also been developed and are generally used as diagnostic plots for estimating when the semi-log straight line should start. With the log-log technique, the measured data are compared with type-curves developed from the theoretical equations. When a match is obtained between the measured and theoretical data, the reservoir transmissivity, storativity and well skin factor can be estimated. Unfortunately, the curves are not unique and it is possible to obtain more than one match to the measured data. This technique is better applied to observation well data where only one curve is used for matching. This is discussed in more detail in section 4.2.2.

4.2.2 Long-Term Injection Test

The data from the injection and observation wells are to be collected on a five minute basis during the first day and then on an hourly basis for the remainder of the test, as specified in the Task 3 report. The reporting form to be provided for the injection well is included in Appendix A. The downhole pressure data from the observation wells will be automatically recorded using the "Mini-Max" data logger units.

At the end of the long-term injection test, a pressure falloff test will be conducted in the injection well using the same program as

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at the end of the short-term injection test. The pressure data will then be analyzed in the same way as for the short-term completion test to obtain the reservoir transmissivity and well skin factor.

The pressure data collected from the observation wells will be analyzed using standard techniques for a multiple well interference test. As with pressure falloff test data, the analysis of interference test data is based on the use of semi-log and log-log plots.

The log-log plotting technique is used to match the measured data to reservoir type-curves which are based on the solution of the diffusivity equation. For interference testing, there is one basic theoretical curve. On the theoretical curve, dimensionless pressure (p_D) is plotted against dimensionless time (t_D) divided by the square of the dimensionless distance (r_D^2). These quantities are defined as follows:

$$p_D = \frac{kh\,\Delta p}{141.2\,q\mu} \tag{5}$$

$$\frac{t_D}{r_D^2} = \frac{0.0002637\,kh\Delta t}{\phi\mu c_t h r^2} \tag{6}$$

where: r = distance from injection well to the observation well (feet).

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The measured data are plotted as pressure change (Δp) versus time (Δt) and the resulting curve is matched to the theoretical curve. When a match between the two is found, the reservoir transmissivity and storativity can be estimated from the pressure and time match points, respectively using the following equations:

$$kh = 141.2q\mu \left(\frac{p_D}{\Delta p} \right) \tag{7}$$

$$\phi c_t h = \frac{0.0002637\ kh}{\mu} \left(\frac{\Delta t}{r^2} \right) \left(\frac{r_D^2}{t_D} \right) \tag{8}$$

The data can also be analyzed using semi-log techniques where the measured pressure is plotted against the log of time since injection started. From this plot, it should be possible to determine the location of the semi-log straight line and the reservoir transmissivity is calculated from the same equation used for the pressure falloff analysis (equation 3). The storativity can then be calculated from:

$$\phi c_t h = \frac{kh}{r^2 \mu}\ \text{antilog} \left(\frac{p_i - p_{1hr}}{m} - 3.23 \right) \tag{9}$$

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Note that the values of transmissivity and storativity calculated from the semi-log analysis should be in reasonable agreement with the results of the log-log analysis.

It is possible that the measured data will depart significantly in shape from the theoretical curve. If this is the case, the reservoir may be significantly more complicated than the ideal reservoir on which the theoretical model is based. However, the way in which the data deviate from the ideal model can provide additional qualitative information on the geometry of the geothermal system.

4.3 Flow Testing

4.3.1 Data Collection

As mentioned previously, the SOH wells may be allowed to be flow tested for short periods of time. A detailed description of the flow testing procedure is given in the Task 3 report. The data collected manually shall be entered into the appropriate data form, a sample of which is provided in Appendix A. The wellhead temperature and pressure, the flowline pressure at the upstream tap of the orifice plate and the weir crest height, will be read directly from gauges and recorded manually on an hourly basis. Although the orifice differential pressure and the lip pressure will be recorded automatically by the Barton recorder, a spot measurement of both parameters should be logged on the data form, also on an hourly basis with the rest of the parameters. The weir temperature will be recorded once a day, during the first three days of the test. During the course of the test,

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chemical samples of fluids and gases shall be collected at selected time intervals, following the procedure detailed in Chapter 3.

The data will be entered in a computer spreadsheet and transmitted to GeothermEx on a daily basis, in order to introduce changes, if required, during the course of the test. The flowing parameters will be reduced and processed to calculate steam and water flow rates and total fluid enthalpy values, using the methodology presented below.

At the end of the flow period, a build-up survey will be conducted, following the procedure described in the Task 3 report. The downhole pressure data will be analyzed using the same methodology described in section 4.2.1 for the fall-off test, in order to obtain values for the reservoir transmissivity and skin factor.

4.3.2 Data Analysis

The equipment shown in the test setup, which is, described in the Task 3 report, allows production data to be obtained that can be analyzed by the James lip pressure method, using both the orifice and weir calculation techniques. Both methods use two independent measurements to obtain two simultaneous equations relating total mass flow rate and enthalpy. These equations are then solved simultaneously to obtain the discharge parameters for the well.

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Orifice Method

For the orifice method, the equation used to calculate mass flow rate from orifice pressure differential data in a single phase fluid is:

$$W = 3{,}600 \frac{C}{\left[1-\beta^4\right]^{1/2}} Y \frac{\pi}{4} \frac{d^2}{144} \left[2g\,(p_1-p_2)\rho_1\right]^{1/2} \quad (10)$$

where:
- W = mass flow rate (lbs/hr);
- C = discharge coefficient;
- d = orifice internal diameter (inches);
- β = diameter ratio (d/D);
- D = internal pipe diameter (inches);
- Y = orifice expansion factor;
- ρ_1 = fluid density (lb/ft^3);
- g = acceleration due to gravity (ft/s^2);
- p_1 = pressure at upstream manometer tapping (psig); and
- p_2 = pressure at downstream manometer tapping (psig).

When using orifice plates to measure two-phase flow rates, the general orifice equation (equation 10), is used with a modified density that accounts for the two-phase mixture. The method was first presented by James in 1966, who conducted a large number of experiments on metering two-phase flows using orifice plates on a geothermal well in Wairakei, New Zealand. The flow rate from the well was measured using a separator and single phase orifice plates to independently measure the separated steam and water flows. The steam and water were then

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recombined and flowed through a two-phase orifice plate equipped with radius taps installed in the discharge line.

Knowing the total mass flow rate, James was able to calculate the effective two-phase density using equation 10. From the effective density and knowing the orifice upstream conditions, the effective steam fraction at the orifice upstream pressure was also calculated. The experiments were conducted over a range of enthalpy values from approximately 270 to 810 BTU/lbm and for dry saturated steam. Based on these calculations, James obtained a very good empirical correlation between the actual steam fraction and the effective steam fraction at the orifice upstream pressure. The results gave the following correlation:

$$x_m = x^{1.5} \tag{11}$$

where: x_m = effective steam fraction or quality; and
x = actual steam fraction at orifice upstream pressure.

Combining the above relationship with equation 10 gives the following equation for a two-phase orifice plate:

$$W_{tp} = \frac{154.3\ d^2\ Y_{tp}}{\left[\ 1-\beta^4\ \right]^{1/2}} \left[\ \frac{\phi_{tp}}{x^{1.5}\ (\nu_s-\nu_w) + \nu_w}\ \right]^{1/2} \tag{12}$$

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where:

W_{tp} = total mass flow rate of two-phase fluid (lb/hr);
Y_{tp} = James' two-phase orifice expansion factor;
ϕ_{tp} = differential pressure across the orifice measured in inches of mercury under water;
ν_s = specific volume of steam (ft^3/lb); and
ν_w = specific volume of water (ft^3/lb).

Using equation 12, the two-phase flow rate can be calculated from the pressure differential measured with an orifice plate, provided that the enthalpy of the two-phase mixture is available to calculate the steam fraction at the orifice upstream pressure. The enthalpy can either be measured independently or, if a second relationship between enthalpy and total flow rate is available, it can be solved simultaneously with equation 12 to find the total flow rate and enthalpy.

For the test setup shown in the Task 3 report, the second relationship between total mass flow rate and enthalpy is provided by the lip pressure or critical flow measurements obtained from the James discharge pipe. James presented the following correlation based on experimental data from flow tests using 2.9, 6.06 and 7.9 inch diameter discharge pipes, that relates enthalpy and flow rate to the measured lip pressure for the discharge of two-phase mixtures to the atmosphere:

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$$W_{tp} = \frac{223{,}800 \cdot p_c^{0.96}\, d_c^2}{h_t^{1.102}} \qquad (13)$$

where: W_{tp} = total mass flow rate of two-phase fluid (lb/hr);
p_c = lip pressure at end of discharge pipe (psia);
d_c = diameter of discharge pipe (inches); and
h_t = total fluid enthalpy (BTU/lbm).

Equation 13, which is based on experiments conducted over the enthalpy range from 235 to 1,204 BTU/lbm, can then be solved simultaneously with equation 12 to obtain the required flow rate and enthalpy data. The resulting equation in terms of enthalpy is:

$$h_t^{1.102} = 1{,}450.4 \cdot \frac{d_c^2}{d^2} \cdot \frac{p_c^{0.96}}{Y_{tp}} \left[1-\beta^4 \right]^{1/2} \left[\frac{x^{1.5}(\nu_s-\nu_w) + \nu_w}{\phi_{tp}} \right]^{1/2} \qquad (14)$$

Note that the steam fraction (x) at the upstream orifice pressure is also dependent on the total fluid enthalpy (h_t) and is calculated from:

$$x = \frac{h_t - h_w}{h_s - h_w} \qquad (15)$$

where: h_t = total fluid enthalpy (BTU/lbm);

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h_w = water enthalpy at orifice upstream pressure (BTU/lbm); and

h_s = steam enthalpy at orifice upstream pressure (BTU/lbm).

Therefore equations 14 and 15 must be solved using an iterative process to find the fluid enthalpy from the measured data. The total flow rate (W_{tp}) is then found from either equation 12 or 13.

It may be necessary to correct the calculated enthalpy if the gas concentration in the total discharge exceeds 1/2% by weight. If the correction is not made, the calculated enthalpy and flow rate will be erroneously high. Grant, *et al.* suggested that the correction to the calculated enthalpy be given by the following equation:

$$\Delta h_t = h_{fac} \cdot f_{lip} \qquad (16)$$

where: Δh_t = correction factor for calculated enthalpy (BTU/lbm);
h_{fac} = enthalpy factor calculated from equation 18; and
f_{lip} = mass fraction of gas in the vapor phase at the measured lip pressure.

The mass fraction of gas is found from gas samples or from measured gas/steam ratios, with the mass fraction corrected for the difference between the sampling pressure and the measured lip pressure. Assuming all gas is in the vapor phase:

$$f_{lip} = f_1 \cdot x_1 / x_{lip} \qquad (17)$$

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where: f_1 = mass fraction of gas in the vapor phase at the sampling pressure;
x_1 = steam fraction or quality at the sampling pressure; and
x_{lip} = steam fraction or quality at the measured lip pressure.

The steam fractions are calculated using the uncorrected enthalpy (h_t), with the water and steam enthalpies found from steam tables at the appropriate pressures.

The enthalpy factor (h_{fac}) in equation 16 is calculated from:

$$h_{fac} = h_t \cdot (1{,}152.6 - h_t)/(1{,}322.86 - 0.11h_t) \qquad (18)$$

The corrected enthalpy is given by:

$$h_{corr} = h_t - \Delta h_t \qquad (19)$$

Weir Method

For the weir method, the water flow from the atmospheric silencer is measured using a weir. For a V-notch weir, which is commonly used in this application, the water flow rate is proportional to $H^{2.5}$, where H is the head above the weir notch. This is a general relationship and each weir has a different discharge coefficient depending primarily on the angle of the notch. For a 90° V-notch weir:

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$$W_w = 2.481H^{2.5} \quad (20)$$

where: W_w = volumetric water flow rate (ft^3/s); and
H = head of water above weir notch (ft).

Knowing the density of the water in the weirbox, the above volume flow rate can then be converted to a mass flow rate.

The steam fraction (x') at atmospheric pressure is given by:

$$x' = \frac{h_t - h_w'}{h_s' - h_w'} \quad (21)$$

where: h_t = total fluid enthalpy (BTU/lbm);
h_w' = water enthalpy at atmospheric pressure (BTU/lbm); and
h_s' = steam enthalpy at atmospheric pressure (BTU/lbm).

From a mass balance on the atmospheric silencer:

$$W_{tp} = W_w/(1-x')$$

$$= \frac{W_w \cdot (h_s' - h_w')}{(h_s' - h_t)} \quad (22)$$

where: W_w = mass water flow rate from weir measurements (lb/hr).

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Equation 22 provides a relationship between total mass flow rate and enthalpy that can be solved simultaneously with the lip pressure relationship (equation 13) to give the total mass flow rate and enthalpy.

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TABLES

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Table 3.1 Chemical Geothermometers

SILICA GEOTHERMOMETERS
(SiO_2 in mg/kg)

- Quartz, conductive cooling (*after* Fournier and Potter)

$$T°C = -42.1981 + 0.288313*(SiO_2) - 0.000366863*(SiO_2)^2$$
$$+3.16647*(10^{-7})*(SiO_2)^3 + 77.03438*\log_{10}(SiO_2)$$

for $SiO_2 \geq 6.4$ and $SiO_2 \leq 750$ mg/kg ($T \leq 330°C$)

(Note: corrections need to be applied for high pH or high density fluids)

- Quartz, after steam loss at 100°C (Arnorsson, *after* Fournier and Potter)

$$T°C = -53.500 + 0.11236*(SiO_2) - 0.0005559*(SiO_2)^2$$
$$+0.1772*(10^{-7})*(SiO_2)^3 + 88.390*\log_{10}(SiO_2)$$

for $T \leq 330°C$.

- Chalcedony, conductive cooling *after* Fournier and Potter

$$T°C = 1032/[4.69 - \log_{10}(SiO_2)] - 273.15$$

for T = 25-250°C

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Table 3.1 Chemical Geothermometers, page 2

- Chalcedony, conductive cooling (*after* Arnorsson)

$$T°C = 1112/[4.91 - \log_{10}(SiO_2)] - 273.15$$

for T = 25-250°C (apply with caution above 180°C)

- Chalcedony, after steam loss at 100°C (*after* Arnorsson)

$$T°C = 1264/[5.31 - \log_{10}(SiO_2)] - 273.15$$

for T = 100-250°C (apply with caution above 180°C)

- Amorphous silica, conductive cooling (*after* Fournier)

$$T°C = 731/[4.52 - \log_{10}(SiO_2)] - 273.15$$

for T = 0-250°C

(Note: corrections need to be applied for high density fluids)

Na-K-Ca GEOTHERMOMETERS
(Na, K, Ca in moles/kg H_2O)

- *after* Fournier and Truesdell

$$T°C = 1647/[\log_{10}(Na/K) + \beta * \log_{10}(\sqrt{Ca/Na}) + 2.24] - 273.15$$

$T < 100°C$, $\beta = 4/3$
$T > 100°C$, $\beta = 1/3$

$T > 4°C$ and $T < 340°C$

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Table 3.1 Chemical Geothermometers, page 3

- *after* Benjamin and others

$$T°C = -22200/[\log_{10}(Na/K) - 6.3*\log_{10}(\sqrt{Ca/Na}) - 64.2] - 273.15$$

for $(\sqrt{Ca/Na}) > 1$ and $T < 100°C$

$$T°C = 1416/[\log_{10}(Na/K) - 0.055*\log_{10}(\sqrt{Ca/Na}) - 1.69] - 273.15$$

for $(\sqrt{Ca/Na}) < 1$ and/or $T > 100°C$

- *after* Ballantyne and Moore (Smectite-Illite)

$$T°C = 1145/[0.35*\log_{10}(Na) + 0.175*\log_{10}(Ca) - 0.75*\log_{10}(K) + 1.51] - 273.15$$

for $T > 100°C$

Na/K GEOTHERMOMETERS
(Na, K, in mg/kg or mg/l)

- *after* Fournier

$$T°C = 1217/[\log_{10}(Na/K) + 1.483] - 273.15$$

for $T > 150°C$

- *after* Arnorsson

$$T°C = 933/[\log_{10}(Na/K) + 0.993] - 273.15$$

for $T = 25 - 250°C$

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Table 3.1 Chemical Geothermometers, page 4

$$T°C = 1319/[\log_{10}(Na/K) + 1.699] - 273.15$$

for T = 250 - 350°C

- *after* Giggenbach

$$T°C = 1390/[\log_{10}(Na/k) + 1.75] - 273.15$$

K-Mg GEOTHERMOMETER
(K, Mg in mg/kg)

- *after* Giggenbach

$$T°C = 4410/[13.95 - \log_{10}(K^2/Mg)] - 273.15$$

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APPENDICES

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APPENDIX A

Sample Data Forms

GeothermEx, Inc.

Geothermal Well Log

COMPANY _____

WELL _____ FIELD _____

COUNTY/STATE/COUNTRY _____

LOCATION _____

LITHOLOGY

HYDROTHERMAL ALTERATION

MINERAL ABBREVIATIONS

Q = QUARTZ
C = CALCITE
P = PYRITE
E = EPIDOTE

ELEVATION _____ KB _____ GL
SPUD DATE _____ TD DATE _____
DRILLED DEPTH _____ VERT. DEPTH _____
BOTTOMHOLE LOCATION _____
DRILLING FLUID _____
_____
INTERVAL LOGGED _____ to _____
LOG SCALE _____
REMARKS _____
_____
_____
_____

COMPANY REPRESENTATIVE _____
DRILLING CONTRACTOR _____
MUD COMPANY _____
LOGGED BY _____

LOST CIRCULATION ZONES

FLUID ENTRIES

HOLE DIAMETER

_____ to _____
_____ to _____
_____ to _____
_____ to _____
_____ to _____

CASING RECORD

_____ to _____
_____ to _____
_____ to _____
_____ to _____
_____ to _____

ABBREVIATIONS

DRILLING PENETRATION RATE

__ ft/hr __ min/ft

DEPTH

LITHOLOGY

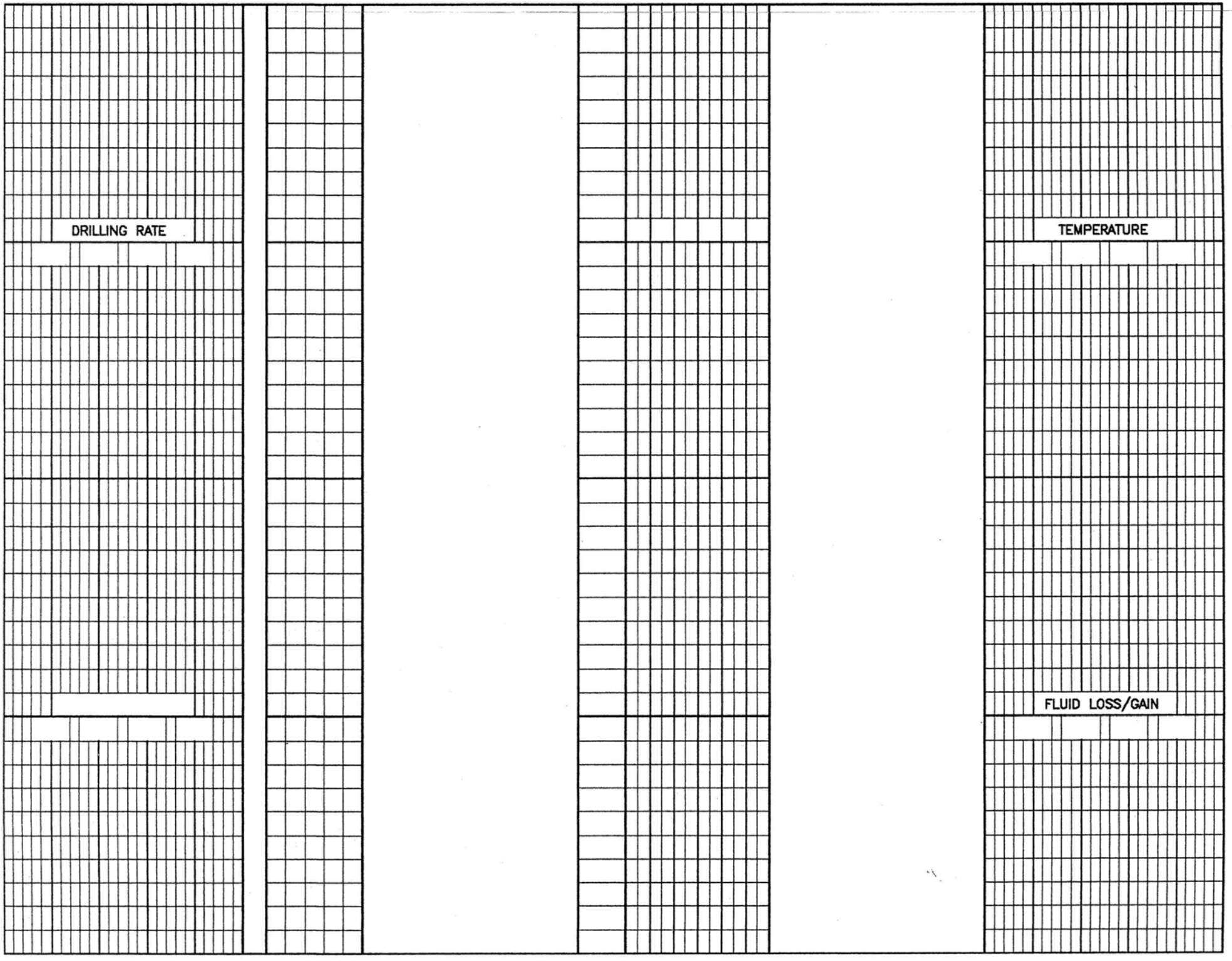
ALTERATION

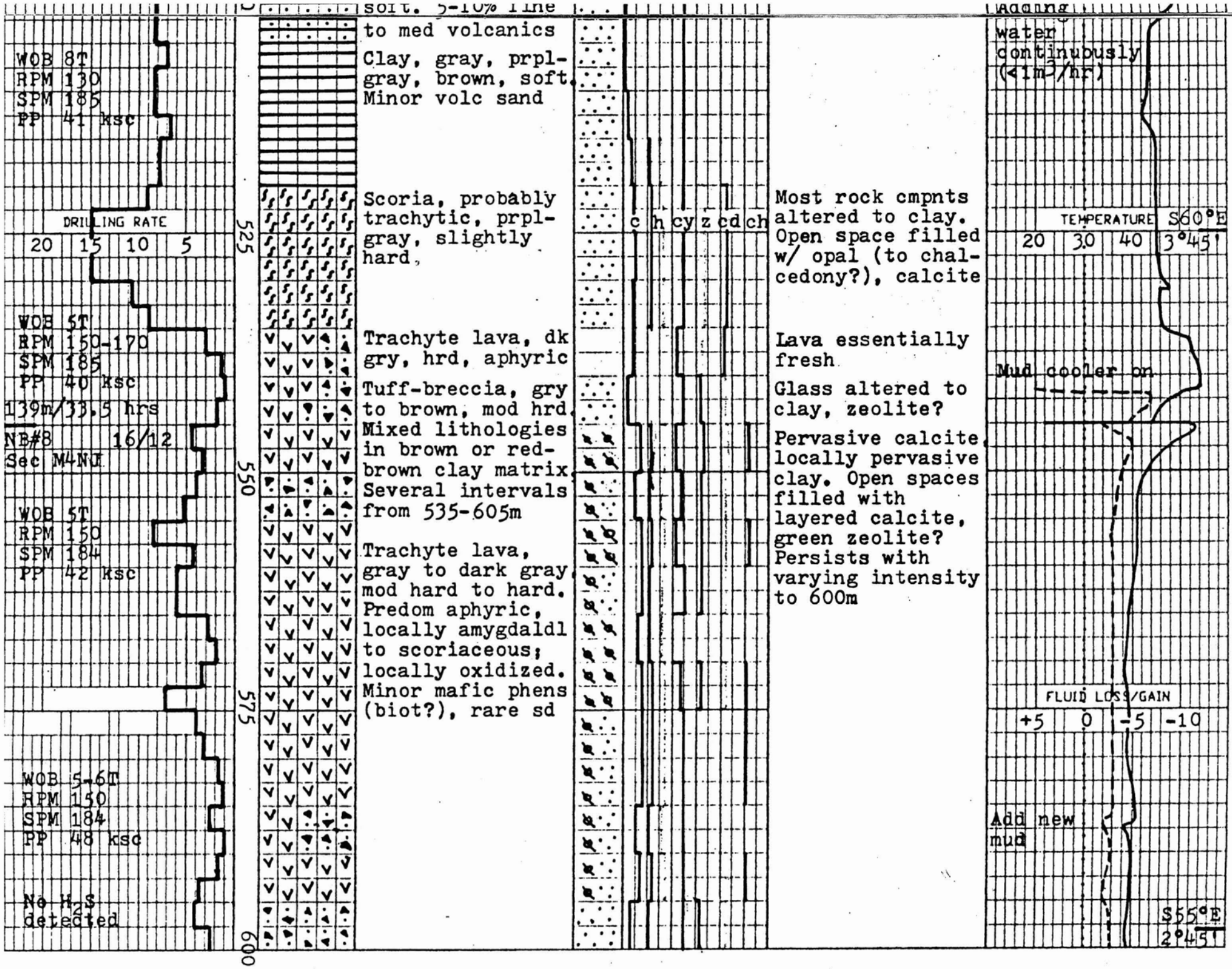
TYPE

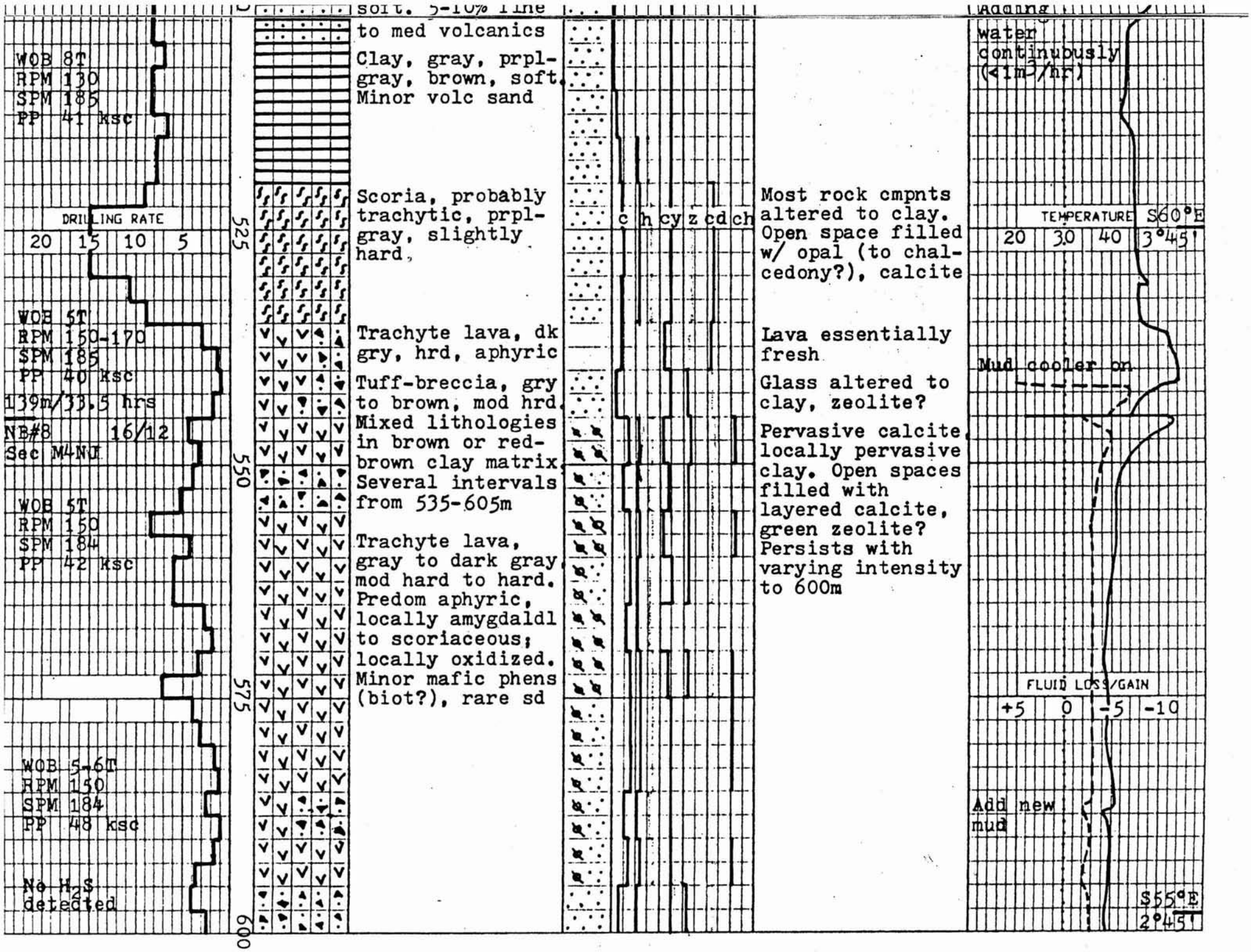
TEMPERATURE _°C _°F

– – – IN ——— OUT

FLUID LOSS/GAIN


DRILLING RATE
TEMPERATURE
FLUID LOSS/GAIN


soft. 5-10% fine
to med volcanics
Clay, gray, prpl-gray, brown, soft. Minor volc sand
Scoria, probably trachytic, prpl-gray, slightly hard.
Trachyte lava, dk gry, hrd, aphyric
Tuff-breccia, gry to brown, mod hrd. Mixed lithologies in brown or red-brown clay matrix. Several intervals from 535-605m
Trachyte lava, gray to dark gray, mod hard to hard. Predom aphyric, locally amygdaldl to scoriaceous; locally oxidized. Minor mafic phens (biot?), rare sd
c h cy z cd ch
Most rock cmpnts altered to clay. Open space filled w/ opal (to chalcedony?), calcite
Lava essentially fresh
Glass altered to clay, zeolite?
Pervasive calcite, locally pervasive clay. Open spaces filled with layered calcite, green zeolite? Persists with varying intensity to 600m
Adding water continuously (<1m³/hr)
TEMPERATURE S60°E
20 30 40 3°45'
Mud cooler on
FLUID LOSS/GAIN
+5 0 -5 -10
Add new mud
S55°E
2°45'
WOB 8T
RPM 130
SPM 185
PP 41 ksc
DRILLING RATE
20 15 10 5
WOB 5T
RPM 150-170
SPM 185
PP 40 ksc
139m/33.5 hrs
NB#8 16/12
Sec M4NU
WOB 5T
RPM 150
SPM 184
PP 42 ksc
WOB 5-6T
RPM 150
SPM 184
PP 48 ksc
No H2S detected
525
550
575
600


soft. 5-10% fine
to med volcanics
Clay, gray, prpl-gray, brown, soft. Minor volc sand
Scoria, probably trachytic, prpl-gray, slightly hard.
Trachyte lava, dk gry, hrd, aphyric
Tuff-breccia, gry to brown, mod hrd. Mixed lithologies in brown or red-brown clay matrix. Several intervals from 535-605m
Trachyte lava, gray to dark gray, mod hard to hard. Predom aphyric, locally amygdaldl to scoriaceous; locally oxidized. Minor mafic phens (biot?), rare sd
c h cy z cd ch
Most rock cmpnts altered to clay. Open space filled w/ opal (to chalcedony?), calcite
Lava essentially fresh
Glass altered to clay, zeolite?
Pervasive calcite, locally pervasive clay. Open spaces filled with layered calcite, green zeolite? Persists with varying intensity to 600m
Adding water continuously (<1m³/hr)
TEMPERATURE S60°E
20 30 40 3°45'
Mud cooler on
FLUID LOSS/GAIN
+5 0 -5 -10
Add new mud
S55°E
2°45'
WOB 8T
RPM 130
SPM 185
PP 41 ksc
DRILLING RATE
20 15 10 5
WOB 5T
RPM 150-170
SPM 185
PP 40 ksc
139m/33.5 hrs
NB#8 16/12
Sec M4NU
WOB 5T
RPM 150
SPM 184
PP 42 ksc
WOB 5-6T
RPM 150
SPM 184
PP 48 ksc
No H2S detected
525
550
575
600

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WEEKLY REPORT - WELLSITE GEOLOGY

WELL: _____ DATE: _____

DEPTH: _____ to _____ ft

SUMMARY OF ACTIVITIES: _____

FORMATIONS ENCOUNTERED: _____

HYDROTHERMAL ALTERATION: _____

TEMPERATURE INDICATIONS: _____

PERMEABILITY INDICATIONS: _____

INTERPRETATION/COMMENTS: _____

PREPARED BY: _____

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DOWNHOLE TEMPERATURE/PRESSURE SURVEY RECORD

Well _____ Date _____ Run no. _____

Hole depth _____ Start time _____ Stop time _____

Hole condition _____

Clock no. _____ Temp. tool _____ Pressure tool _____

Depths from _____ Temp. range _____ Press. range _____

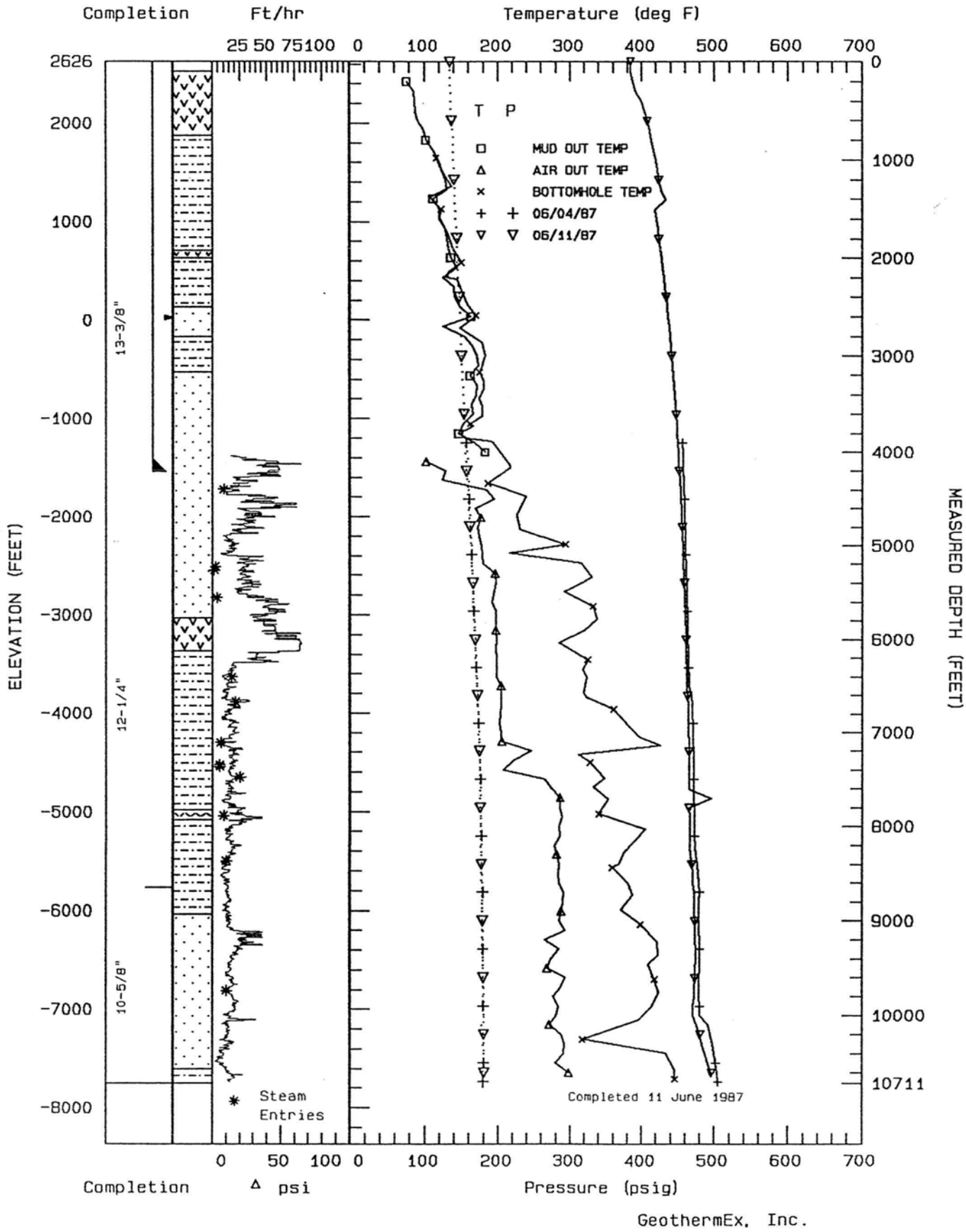
Operated by _____ Read by _____ Air temp _____ MRT _____

Time on bottom _____ Time off bottom _____

Time	Depth	Temp defl	Temperature	Press defl	Pressure

Remarks _____

Downhole summary plot from a well at The Geysers



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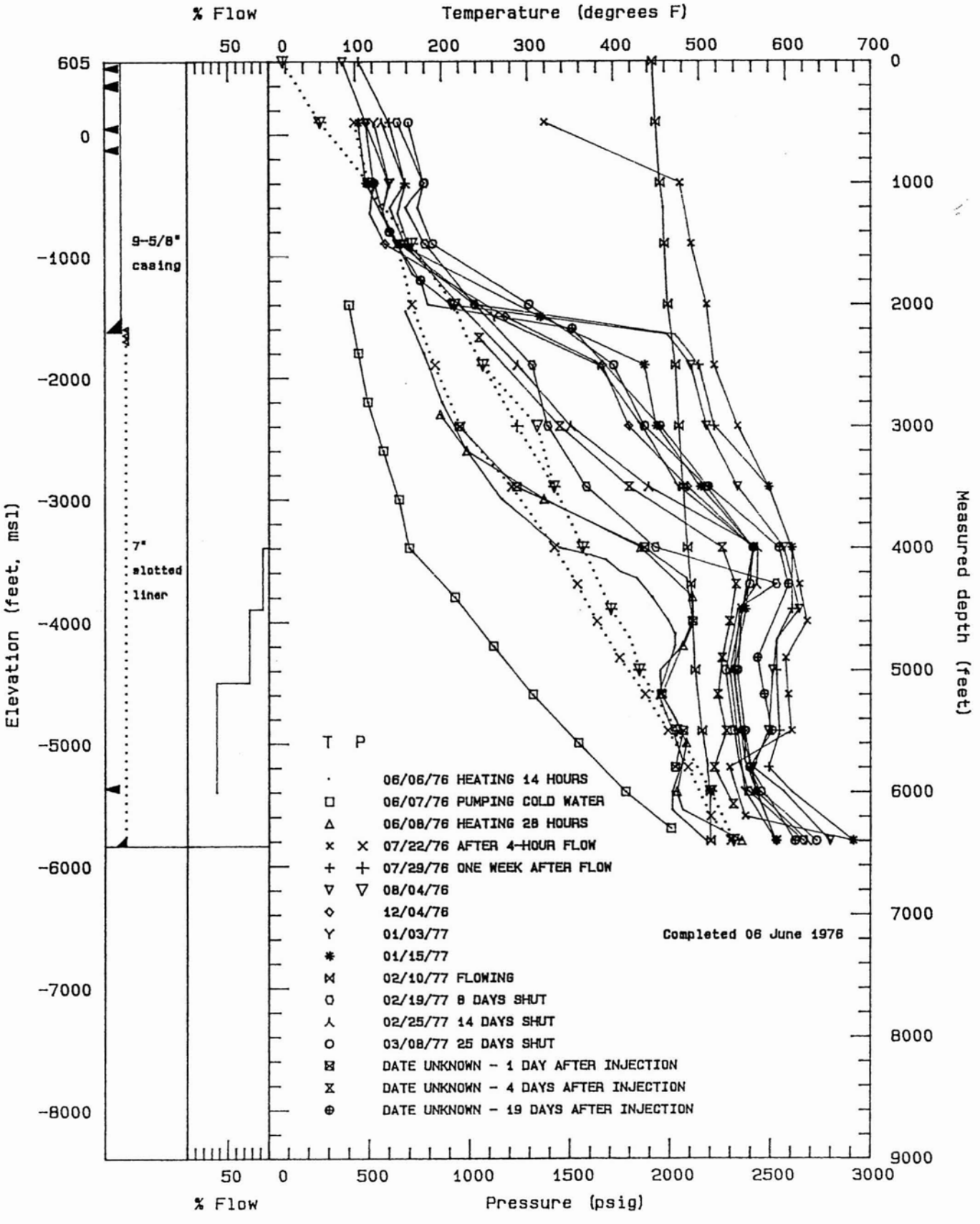
DOWNHOLE SUMMARY PLOT, WELL HGP-A



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09-09-1988 T1.PLT

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PRESSURE BUILDUP/FALLOFF DATA SHEET

Well _____ Injecting/Flowing since _____
Buildup _____ Falloff _____ Details of rate changes _____
Shut-in date _____ _____
Shut-in time _____ _____
Pressure chamber depth _____ T/P surveys run _____

Δt (hrs:min)	TIME	WHP (psig)	DHP (psig)
	** 1-MINUTE INTERVALS **		
00:00			
00:01			
00:02			
00:03			
00:04			
00:05			
00:06			
00:07			
00:08			
00:09			
00:10			
00:11			
00:12			
00:13			
00:14			
00:15			
	** 5-MINUTE INTERVALS **		
00:20			
00:25			
00:30			
00:35			
00:40			
00:45			
00:50			
00:55			
01:00			

Δt (hrs:min)	TIME	WHP (psig)	DHP (psig)
	** 15-MINUTE INTERVALS **		
01:15			
01:30			
01:45			
02:00			
02:15			
02:30			
02:45			
03:00			
03:15			
03:30			
03:45			
04:00			
	** 1-HOUR INTERVALS **		
05:00			
06:00			
07:00			
08:00			
09:00			
10:00			
11:00			
12:00			

INJECTION TEST DATA SHEET

GeothermEx, Inc.

Well _____ Shut-in WHP _____ Data collected by _____
Test start date _____ Shut-in WHT _____ Test witnessed by _____
Test start time _____ Pressure chamber depth _____ Units of measurement _____
Remarks/comments (rate changes, T/P surveys, etc.) _____

Time	Wellhead Pressure	Wellhead Temperature	Orifice Upstream Pressure	Differential Pressure	Injection Flow Rate	Tank Level

FLOW TEST DATA SHEET
GeothermEx, Inc.

Page ____ of ____

Well _____ Shut-in WHP _____ Data collected by _____
Test start date _____ Shut-in WHT _____ Test witnessed by _____
Test start time _____ Pressure chamber depth _____ Units of measurement _____
Remarks/comments (rate changes, T/P surveys, etc.) _____

Time	Wellhead Pressure	Wellhead Temperature	Orifice Upstream Pressure	Differential Pressure	Lip Pressure	Weir Box Water Level	Weir Box Flow Rate	Weir Box Temperature

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OBSERVATION WELL DATA SHEET

Observation well ____________________
Active well ____________________
Test start date ____________________
Test start time ____________________
Observation well start date ____________
Observation well start time ____________
Pressure chamber depth ____________
Units of measurement ____________
Remarks/comments ____

TIME	Wellhead Pressure	Wellhead Temperature	Downhole Pressure

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APPENDIX B

EPRI Mobile Geothermal Laboratory

EPRI MOBILE GEOTHERMAL LABORATORY

Mary E. Jamin, Ph.D.
Rockwell International
Environmental Monitoring & Services Center
2421 W. Hillcrest Drive
Newbury Park, California 91320
805/498-6771

The EPRI Mobile Geothermal Laboratory, CHEMLAB, is a modern analytical laboratory with broad capability for the chemical and physical analysis of geothermal fluids and associated liquid and solid samples such as lubricating oils, scale, and corrosion. Operated in conjunction with a skid-mounted sampling unit, the fluid sampling system, the laboratory can function independently at even the most remote geothermal sites, giving both increased assurance of sample integrity and significant flexibility. When additional capability is required to meet a particular project goal, stable samples may be removed from the site and analyzed at the Rockwell International Laboratories at Canoga Park and Newbury Park, CA.

The fluid sampling system splits the streams within multiphase geothermal fluid to allow collection of discrete samples of brine, steam condensate, and non-condensible gases. The sampling system collects samples in two ways; the temperature is dropped and then the pressure (ΔT or non-flash mode), or the pressure is dropped and then the temperature (ΔP or flash mode). Other types of samples, such as oil or scale, are collected by standard methods appropriate to the particular samples. Samples are stored in polyethylene bottles and stabilized to preserve the desired analytes. Analytical priority has been established so that the least stable species are analyzed first, followed by the more stable species. All samples are fully documented at the time of sampling.

The chemical species and physical properties measured are listed in Table 1. Standard analytical methods such as those of the United States Environmental Protection Agency are used and expected detection limits achieved in dilute samples such as steam condensate. Detection limits may be altered by as much as a factor of ten by the presence of large background ionic concentrations. Alternate methods may be employed to improve detection limits to meet a specific project goal.

A series of tests has been designed to meet the objectives of the mobile laboratory; a signature test is a broad

inclusive characterization of wellhead fluid consisting of the measurement of all properties and species within the normal capacity of the laboratory. Figure 1 is a diagram of the signature test and shows the modes of sample collection, method of sample stabilization and analytical methods used.

TABLE 1

Chemical Species and Physical Properties Measured

A.	Cations:	Ag, Al, As, B, Ba, Ca, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, Na, NH_4, Ni, Pb, Si, Sn, Ti, V, Zn
B.	Anions:	Br, Cl, CO_3, F, HCO_3, I, S, SO_4
C.	Gases:	CO_2, 0_2, H_2, H_2S, N_2, hydrocarbons
D.	Properties:	TDS, conductivity, pH, E_H, turbidity, enthalpy, gas: brine ratio, steam fraction

A tracking test comprises repetitive sampling and analysis at specified times of particular properties and species and is designed to a particular purpose. A special test is generally performed once and may measure any combination of properties and species.

A standard data reporting system, the EPRI Data Base Package, has been devised to ensure comparability of data generated at different sites. Site information and well information, including both history and current conditions, are reported along with sampling information and analytical results. Statistical analyses are performed to estimate the ninety-five percent confidence level.

To ensure the reliability of all generated data, quality control procedures have been developed, including collection of multiple samples or measurement during sampling of unstable species and performance of multiple analyses for most chemical species. Chemical measurements are made against commercially prepared analytical standards and instrument calibration is routinely checked during analytical activities. Control solutions are measured along with standard and sample solutions. All sampling and analytical procedures conform to the standard quality control and quality assurance procedures used in the Rockwell International Environmental Monitoring & Services Center laboratories.

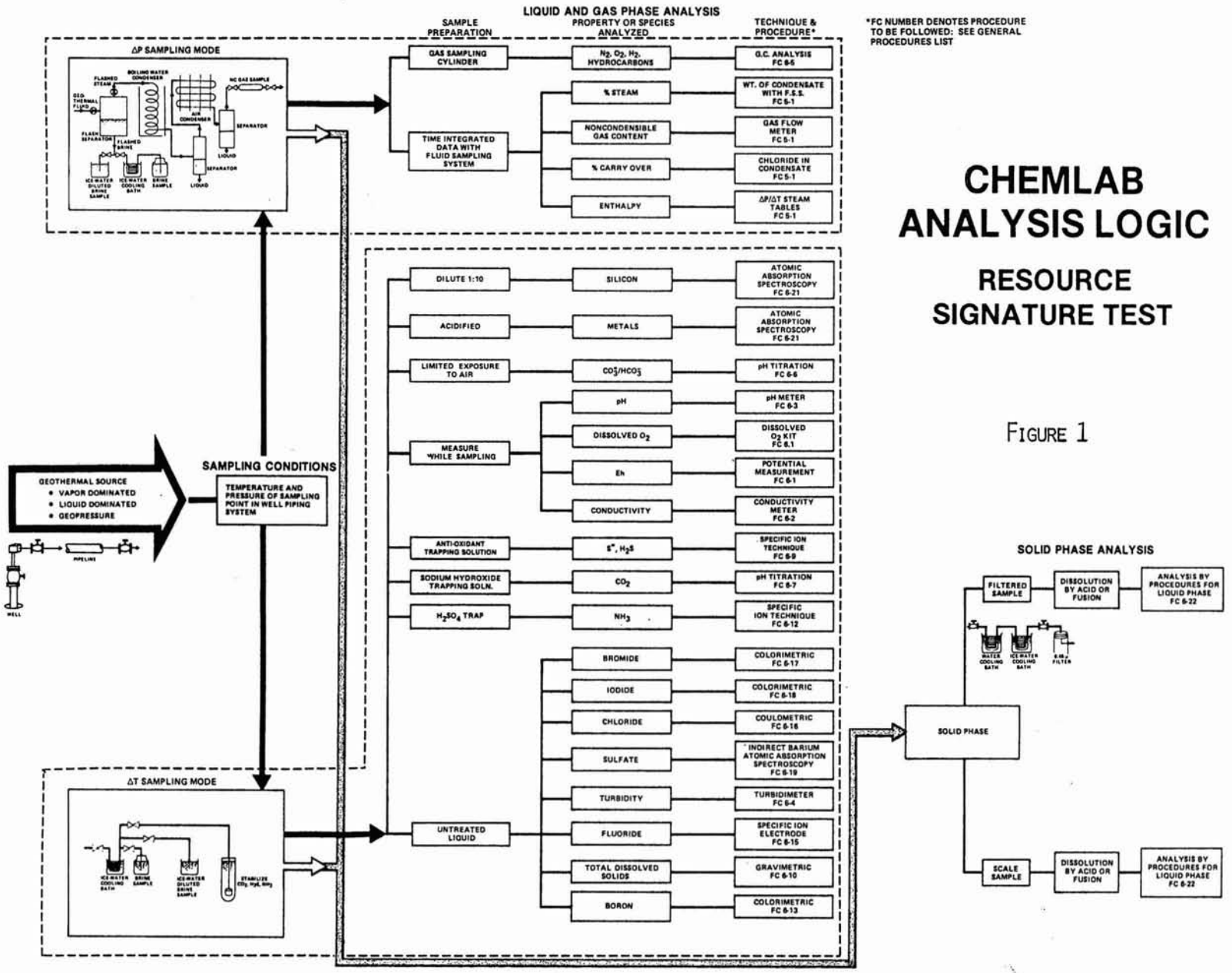
The Mobile Geothermal Laboratory completed extensive readiness testing and began field work in August 1980. The laboratory has visited six sites in the United States, conducting signature tests and supporting field tests: East Mesa, CA; Brazoria County; TX, Brawley, CA; Dixie Valley, NV; Sweetlake, LA; and Milford, UT. Table 2 is a brief summary of data generated during signature testing, and demonstrates the range of fluid constituents encountered.

Future plans include additional signature testing to broaden the EPRI brine data base and additional support of utility field tests.

TABLE 2

Data Generated on CHEMLAB

	Site A	Site B	Site C
TDS, mg/kg	1600	157000	22
pH	7.35	5.21	6.50
gas: brine ratio, L/kg	0.002	2.7	0.089
Cl^-, mg/kg	328	89500	10
Si, mg/kg	127	46.0	Not detected



CHEMLAB ANALYSIS LOGIC

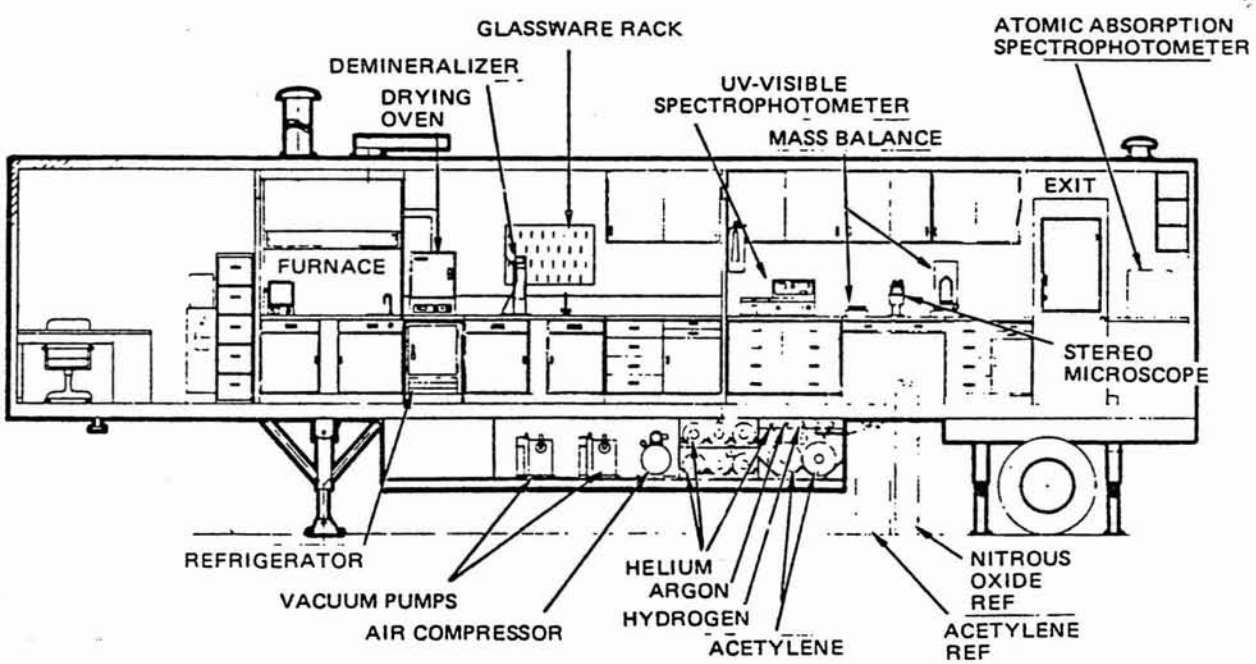
RESOURCE SIGNATURE TEST

FIGURE 1

EPRI CHEMLAB

DESIGNED, BUILT, AND OPERATED BY
ENERGY SYSTEMS GROUP, ROCKWELL INTERNATIONAL

- PROVIDES ACCURATE SAMPLING AND ANALYSIS OF GEOTHERMAL FLUIDS AT THE WELL SITE
- ADVANTAGES:
  - PROMPT ONSITE ANALYSIS MINIMIZES SAMPLE DEGRADATION
  - EARLY AVAILABILITY OF ACCURATE FLUID CHEMICAL AND PHYSICAL ANALYSIS IMPROVES EFFECTIVENESS OF GEOTHERMAL TEST PROGRAMS



EPRI MOBILE GEOTHERMAL LABORATORY – SIDE VIEW 77-JY21-52-23D

TABLE 1

MAJOR ANALYTICAL CHEMISTRY EQUIPMENT FOR CHEMICAL ANALYSIS

EQUIPMENT	TEST CAPABILITY
ATOMIC ABSORPTION SPECTROPHOTOMETER	ANALYSIS OF THE CATION SPECIES: Al, As, Ag, Ba, B, Ca, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Si, Ti, V, Zn
UV-VISIBLE SPECTRO-PHOTOMETER	COLORIMETRIC ANALYSIS: NH_4^+, Br^-, F^-, I^-, $S^=$
COULOMETRIC CHLORIDE METER	ANALYSIS ION MEASUREMENT
AUTOMATIC TITRATING SYSTEM	ANALYSIS OF TOTAL ALKALINITY, CARBONATE-BICARBONATE
DISSOLVED OXYGEN METER	MEASUREMENT OF DISSOLVED OXYGEN
GAS CHROMATOGRAPHIC SYSTEM	ANALYSIS OF NONCONDENSIBLE GASES: CO_2, O_2, H_2, H_2S, N_2, SO_2, CH_4, HYDROCARBONS
pH, SPECIFIC ION METER	MEASUREMENT OF pH AND REDOX POTENTIALS; SPECIFIC ION F^-, NH_4^+
FLUID SAMPLING SYSTEM	SAMPLING NONCONDENSIBLE GASES, STEAM AND GEOTHERMAL BRINE

TABLE 2

MAJOR ANALYTICAL EQUIPMENT FOR PHYSICAL PROPERTY MEASUREMENT

EQUIPMENT	TEST CAPABILITY
• BALANCES	
▪ ANALYTICAL 200 g ± 0.2 mg	WEIGHING FOR CHEMICAL ANALYSIS AND CORROSION SAMPLES REQUIRING ACCURATE RESULTS ON SMALL SAMPLES
▪ TOP LOADING ELECTRONIC 3000 g ± 0.1 g	WEIGHING OF LARGE SAMPLES AND QUICK ROUGH WEIGHINGS
• TURBIDIMETER	DETERMINATION OF TURBIDITY
• CONDUCTANCE METER	CONDUCTANCE MEASUREMENTS ON LIQUID SAMPLES FOR CORRELATION TO TOTAL DISSOLVED SOLIDS CONTENT
• DRYING OVEN	FOR MOISTURE CONTENT, TOTAL DISSOLVED SOLIDS
• STEREOMICROSCOPE	MICROSCOPE EXAMINATION OF SAMPLES